2. BASELINE CONFIGURATION CHOICES

REQUIREMENTS DRIVEN DESIGN

During this pre-conceptual phase, various concepts have been explored and solutions developed with a focus on science and user-needs, costs, and technical risks. In this feasibility study we limit ourselves to presenting the trade studies and risk mitigation plans that most heavily bear on the hard x-ray production. Techniques for producing soft x-rays from cascaded harmonic generation in free-electron lasers are in development and will be described in future reports. The flexible configuration of the recirculating linac simultaneously accommodates several hard and soft x-ray production techniques in parallel.

The facility is designed to provide world-class capabilities in ultra-fast dynamics studies based predominantly on pump-probe experiments. The facility requirements were systematically derived as depicted in Figure 2-1, leading to the key performance parameters listed in Table 2-1. Note that this study is concerned with accelerator design optimized for hard x-ray production - UV and soft x-ray schemes are under development and will be reported in the future.

Table 2-1 Key parameters for an ultrafast x-ray science user facility driven by scientific needs in physics, chemistry and biology.

Multi-user facility: Multiple experimental beamlines
Repetition rate: 10 kHz
Synchronization: better than 50 fs
Broad photon range: 0.02 - 10 keV

- Hard x-rays
  - Tunable: 1 - 10 keV
  - Pulse length: < 100 fs
  - Flux: 3×10^6 (ph/pulse/0.1%BW) @ 1 nC
- Soft x-rays and VUV radiation
  - Tunable: ~ 20 - 1000 eV
  - Pulse length: 50 fs to 2 ps
  - Flux: up to 1012 (ph/pulse/0.1%BW)
- Lasers with temporal and spatial pulse shaping
  - Tunable 267 nm – 3000 nm
- Polarization
  - Switchable LH, RH circular polarization
- Flux stability
  - 10 – 20 % shot-shot variation, average over ~ 10,000 shots/second

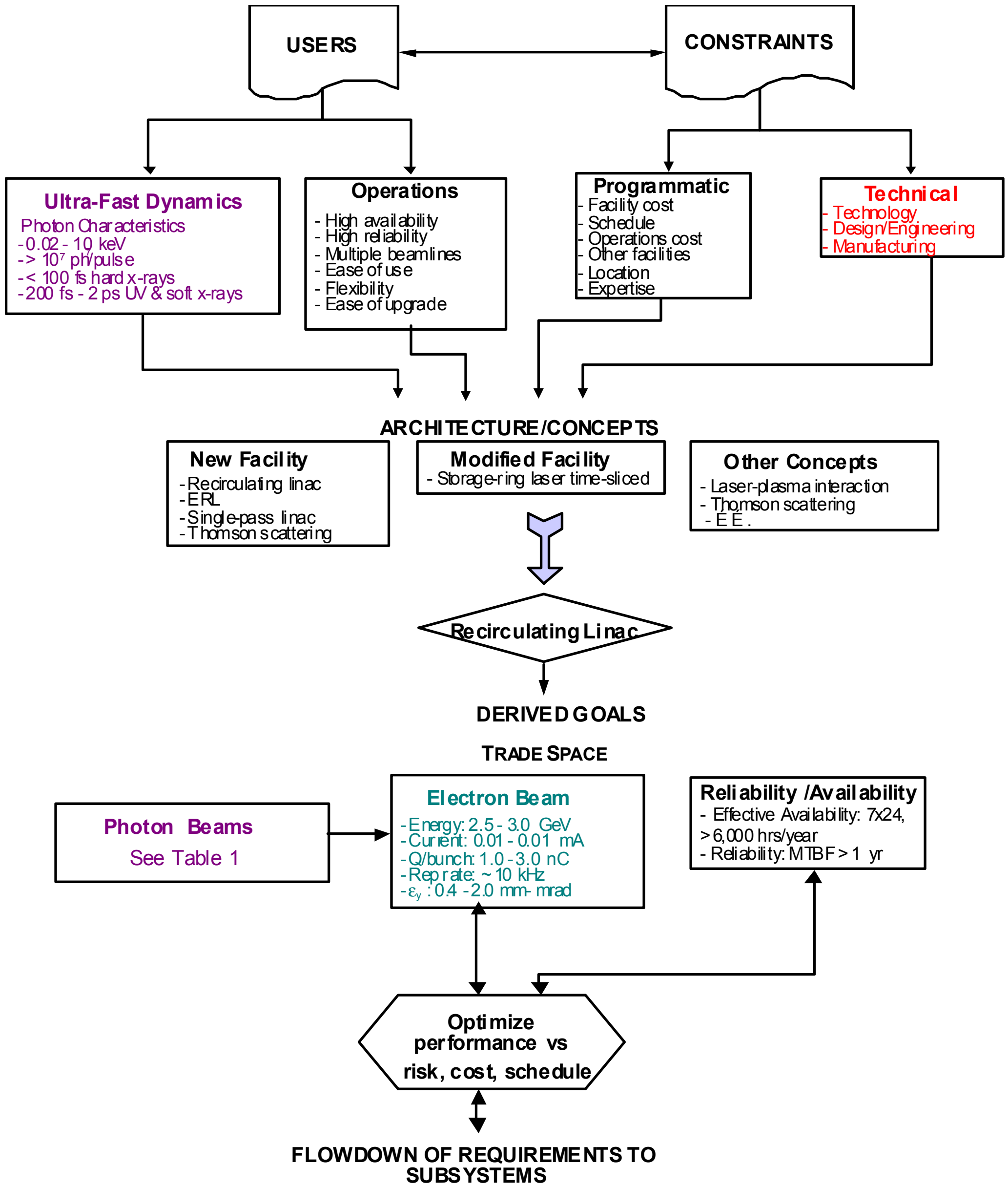

Figure 2-1 Derivation of systems requirements

CONCEPT SELECTION

The choice of a machine concept has a major impact on its development and performance. Several different options have been considered, including other facilities that are being proposed for operation in the same time frame. The proposed technologies may be categorized as follows:

1. ***Upgrades of existing facilities*** - These include implementing laser-slicing in Berkeley Advanced Light Source (ALS) beamlines, the Swiss Light Source (SLS) and others [1].

2. ***Single-Pass Energy Recovery Linacs (ERL)*** - These include the Cornell ERL, the Brookhaven PERL, and Daresbury 4GLS. The radiation is produced following a single pass through the linac, and the kinetic energy of the beam is recovered by returning through the linac [2-4].
3. ***Recirculating linacs*** - These include the Novosibirsk MARS, and the LBNL proposal. The basic concept involves multiple passes through the same linac to achieve the final beam energy [5].
4. ***X-ray Free Electron Lasers (FEL)*** - These include the SLAC LCLS, DESY Tesla XFEL, and the BESSY FEL. They utilize the beam from a single-pass linac to produce highly coherent and intense radiation [6-8].
5. ***Other concepts*** - These include x-ray generation from a laser-plasma interaction, Thomson scattering of laser photons from a relativistic electron beam, etc.

Generation of Femtosecond Hard X-Ray Pulses

The concept of ultra-short radiation pulse production by electron beam manipulation followed by x-ray pulse compression as proposed in Ref. [9] has been developed in this study. The physics for this concept has been described previously in this report, here we note that the photon pulse duration is a function of:

- Square-root of the vertical beam emittance, ε_y
- RF deflection voltage, U
- Inverse of the square-root of deflecting cavity β-function, β_{RF}
- Inverse of the rf wave number (frequency), k_{RF}
- The lattice β-function at the radiation point, β_{ID} (dependent on location of radiation source)
- The radiation opening angle $\sigma_{r'}$ or size σ_r

The implications for the design of the facility are the following:

- A photoinjector that produces a beam with a small emittance
- Flat beam optics in the photo-injector gun that generate a high *x/y* emittance ratio with a resultant very small emittance in one (vertical) direction
- A linac, transport arcs, and lattice that preserve the emittances
- Deflecting cavities that provide a high peak voltage at high frequency
- A photon-production section lattice that allows a large variation in β-functions
- An undulator sufficiently long to produce small divergence in radiation, and a small (diffraction limited) angular divergence

For the hard x-ray applications of this facility, experiments requiring x-ray flux in short pulses are favored over those experiments requiring brightness. In this 1 - 10 keV photon energy range, brightness is traded for short pulse duration. The photon flux on a sample at the end of a beamline is derived from all electrons in a bunch, and so produces a significant increase of ~ 10^4 times what is achievable by the time-slicing method currently being pursued at the ALS and other storage rings.

Another potential technique, which also takes advantage of the correlated electron positions within a bunch, may be to use position-sensitive detectors and the angle-time or coordinate-time correlation of the radiation to simultaneously observe photons with different time delays. This technique would not involve direct compression of the photon pulse.

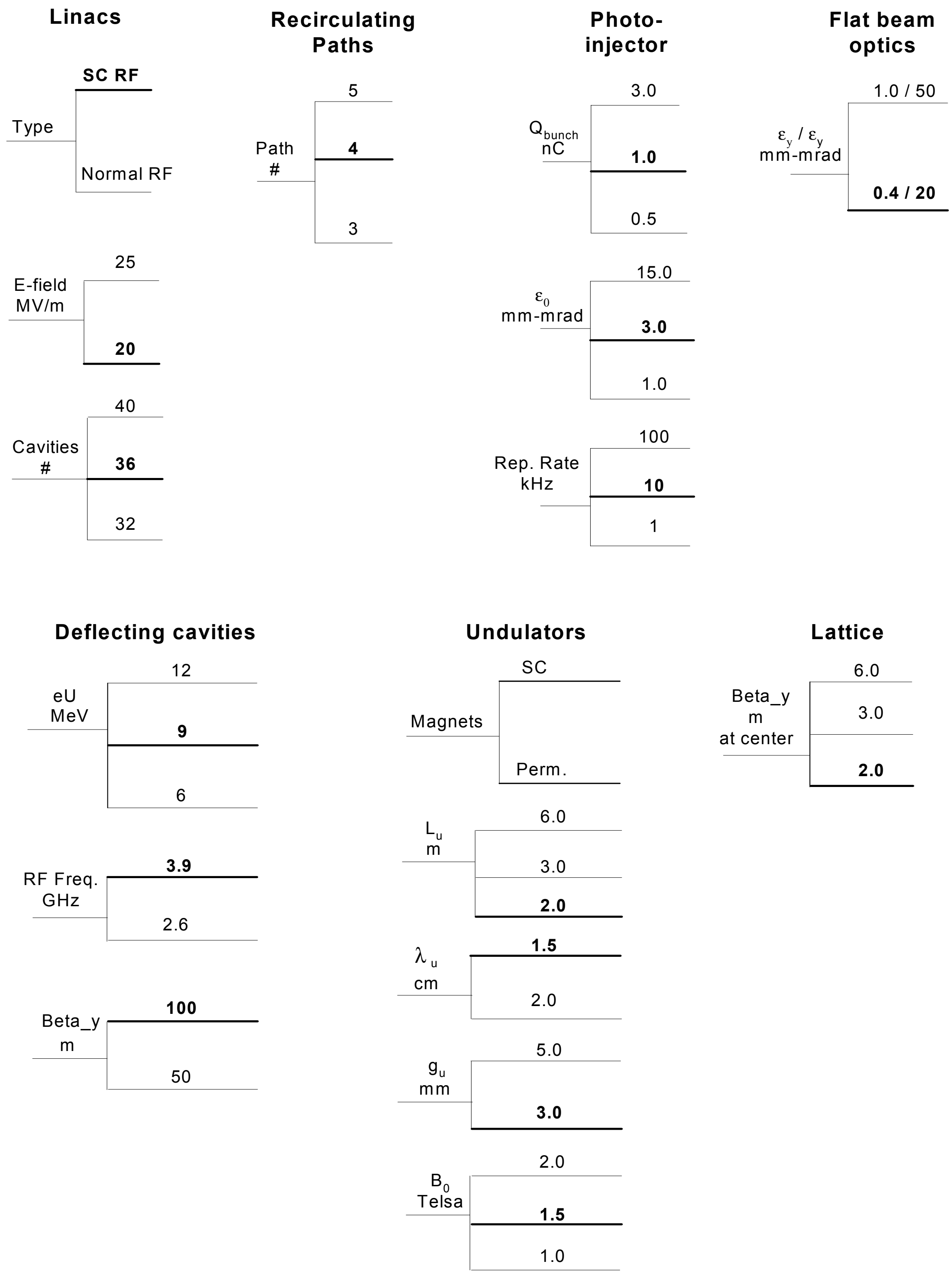

Figure 2-2 Trade-space for baselining the recirculating linac hard x-ray configuration.

DEVELOPMENT OF THE BASELINE CONFIGURATION

A staged low-risk approach has been adopted, in which the baseline design described here incorporates flexibility to allow for (i) upgrades to higher beam energies and/or bunch repetition rate; (ii) possible energy recovery; and (iii) additional insertion devices including free electron lasers (FEL's) as dictated by user needs.

This feasibility study is limited to presenting the trade studies and risk mitigation plans that most heavily bear on the production of hard x-rays. This baseline design is for hard x-ray production, and addition of VUV and soft x-ray components will be addressed in the future.

The facility requires accelerator technology in many areas that has been demonstrated on successful operating machines, but presents some needs for technology development. Recirculating linac designs have been investigated for different configurations of photoinjectors, linacs, undulators, etc, as illustrated in the trade-space represented in Figure 2-2. The heavy lines and bold text represent the present baseline. Some trades studies are still to be completed and further analyses will be performed as the design and technologies evolve. Several key trade studies are summarized below.

Choice of Accelerator RF Technology

Both superconducting and normal conducting rf technologies have been considered for the injector and main linacs. Normal conducting rf linac technology has a proven track record and the fabrication is mature. Superconducting cavities have been demonstrated to achieve accelerating gradients exceeding 25 MV/m at Q_0 over 10^{10} [10]. A normal conducting linac requires ~10^6 times more rf power for the same acceleration gradient than the superconducting linac, but *Q*-values are sufficiently low to allow pulsed operation at 10 kHz repetition rate. Maintaining stability of the multiple pulsed rf systems then introduces problems in producing good beam energy and phase stability. In order to facilitate a bunch rate of 10 kHz, a superconducting linac must operate in a Continuous Wave (CW) mode, while the state-of-the-art TESLA cavities and cryomodules are designed for a low duty factor of approximately 0.7%. Superconducting rf operating in CW mode has advantages of allowing better stabilization of beam energy and phase (timing jitter), and requires significantly reduced rf power systems. The disadvantage is in the requirement for a significant cryogenics system.

Considering issues such as pulse-to-pulse stability (essential to achieve synchronization requirements), rf power requirement, future upgrades, state of technology, availability, and beam dynamics associated with wakefield effects, a superconducting linac has been selected as the baseline for the machine. Further details are found in Chapter 8-Superconducting RF.

The number of cavities needed to achieve an energy gain of greater than 600 MeV per pass depends on the accelerating gradient and the cavity design. For example, the TESLA FEL design uses 9-cell cavities and integrates eight cavities into a single cryomodule. Optimization of the design of the cryomodules is proceeding in parallel with the refrigeration systems design. Details are presented in Chapter 12-Cryogenics.

Recirculating Passes

The number of recirculating paths influences the design, cost, and operation of the facility. As the number of passes increases for a given ultimate beam energy, the cost of the rf subsystem decreases while the cost of the beam transport subsystem increases. The configuration has been designed to minimize project cost for a 2.5 to 3.1 GeV electron beam. Cost estimates at this early stage have inherently high uncertainty and should be treated as

Rough Order of Magnitude (ROM) costs. Figure 2-3 provides the relative dependence of the cost of the relevant subsystems and their sum on the number of passes.

Figure 2-4 shows that the four-pass and five-pass designs achieve the lowest costs, although the minimum is quite shallow. Of particular consideration in selecting either four of five passes as the optimum, we note that design and operations increase in complexity with the number of passes. Based on these results, considerations, and cost uncertainties, the four-pass configuration has been selected as the baseline. The footprint of the baseline machine is approximately 150 x 50 m.

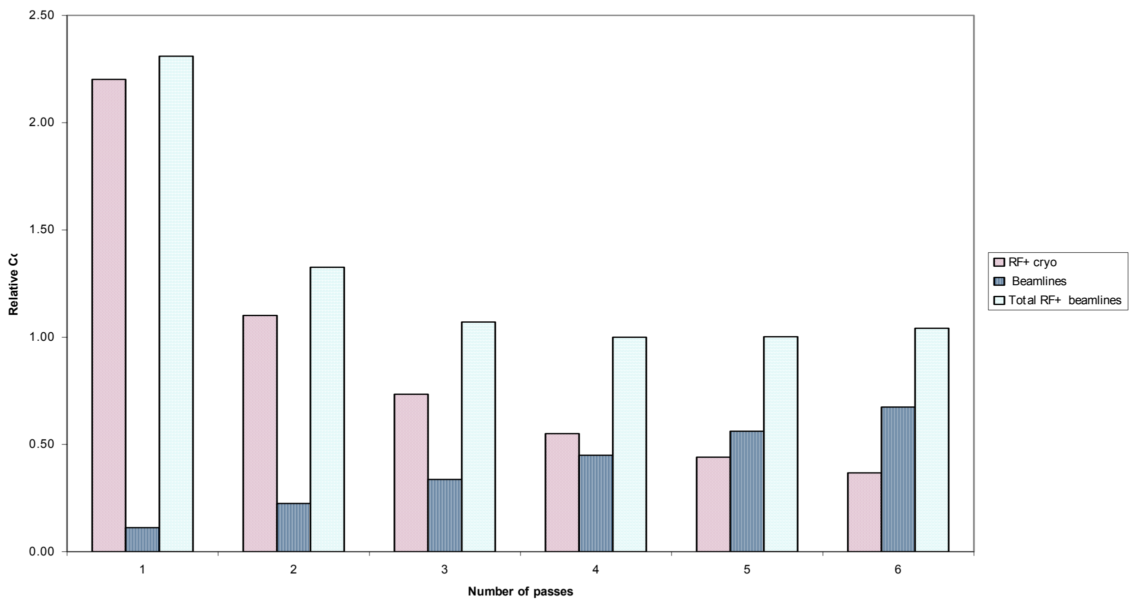

Figure 2-3 Recirculating linac cost trend versus the number of passes

Photoinjector

The photoinjector is probably the most challenging and critical component of the facility. The science needs for a large photon flux in a short pulse drive the photoinjector specifications that include:

- High charge per bunch of initially 1 nC, with a goal of 3 nC
- Small normalized emittance from the rf gun, $\varepsilon_0 \sim 3$ mm-rad, to readily support a flat beam with a low normalized vertical emittance, $\varepsilon_y \sim 0.4$ mm-rad
- High repetition rate, 10 kHz

In addition, to support the reliability and availability demanded of a user-facility, the photoinjector is required to be highly stable in operations and an have operational life of several months. The components of the photoinjector, i.e. the drive laser, photocathode, and rf cavities, are critical elements to achieve these specifications.

The emittance of the beam is a critical accelerator physics parameter that defines the quality of the beam leaving the rf photocathode gun. We note the following characteristics:

- Surface physics and chemistry effects give rise to a distribution in velocities of the electrons as they are emitted from the cathode surface, resulting in the "thermal emittance"
- The emittance increases in a complex manner with the charge per bunch, Q_b due to space-charge effects at low energies
- Space charge effects and resultant emittance growth may be reduced by increasing the gradient of the accelerating electric field near the cathode surface. A larger field accelerates the electrons rapidly and reduces the effects from space-charge forces

There is presently some uncertainty in the reliably obtainable emittance as a function of bunch charge. Our assessment is that space charge effects can be significantly improved through additional R&D and such experiments are being actively pursued.

Emittance growth due to space charge may be controlled by producing a long electron bunch (~20 ps) at the cathode and accelerating rapidly in a high electric field rf gun. Physics and engineering studies indicate that rf cavities providing the required large accelerating fields at a high repetition rate may be fabricated using conventional copper construction and cooling techniques [see Chapter 5-RF Photocathode Gun].

The specified emittance of 3 mm-mrad from the rf photocathode gun is close to that achieved at the exit of the Fermilab A0 gun [11]. An emittance increase of perhaps even a factor of five may be acceptable since the x-ray pulse duration scales as the square-root of emittance. Even in such circumstances, the pulse length remains below 100 fs at 10 keV. Such a trade may be particularly valuable for larger bunch charge where one gains appreciably in flux.

The choice of photocathode material is influenced by thermal emittance, quantum efficiency, availability of laser systems with wavelength matching the cathode work function, reliability, lifetime, and ease of fabrication. The operational lifetime depends on the rate of degradation of the photocathode QE rather than simply its initial value. Experience indicates that adequate lifetimes for a user facility will be achieved through controlled manufacturing techniques and good vacuum and thermal designs.

The baseline design is for a relatively small current of 10 μA. Commercially available lasers have been identified that can support currently viable photocathode options, with some additional requirements in pulse shaping prior to the cathode. Nevertheless, a photocathode with a high quantum efficiency is specified to limit the power and control the cost of the photocathode laser, and reduce the heating of the cathode. Based on the above considerations and the data presented in Chapter 5-RF Photocathode Gun, Cs_2Te has been selected as the baseline photocathode material.

Flat Beam Optics

As described in Chapter 7-Experimental Studies at FNPL the production of electron pulses of ~20 ps duration with *x:y* emittance ratio ~50:1 and with the smaller normalized emittance of less than 1 mm-mrad has been successfully demonstrated at 1 nC bunch charge [12]. Our requirements are within factor of 2 to 3 for emittance and charge of these values, and our baseline design uses the same technique for the production of a flat beam. The approach is to apply a solenoidal magnetic field on the cathode followed by a specially configured skew-quadrupole channel to manipulate the angular momenta of the electrons, resulting in a highly asymmetric transverse emmittance configuration. Further details and investigations into different configurations to minimize the vertical emittance as described in Chapter 8-Flat Beam Adapter.

Deflecting Cavities

To provide position-angle correlation within a bunch, a dipole-mode deflecting cavity operating at a frequency of 3.9 GHz is used, with a transverse voltage of ~ 8.5 MV. Designs with the following objectives have been investigated:

- Take advantage of existing deflecting cavity designs, e.g. developed by FNAL and Cornell University
- Optimize the cavity geometry to minimize the rf power requirements
- Reduce short-range wake-field effects
- Increase the efficiency by operating at higher frequencies

Based on these studies, a 7-cell 3.9 GHz cavity has been selected. We need seven such cavities to obtain a voltage of 8.5 MV, details are presented in Chapter 10-Deflecting Cavities. We may trade this deflecting voltage and frequency with the vertical beta-function in the deflecting rf structure since increasing its value also benefits shorter x-ray pulses.

Undulators

The baseline design uses spontaneous synchrotron radiation produced in undulators as the source of hard x-rays.

Several undulator designs are under consideration, covering a large trade space that considers different magnet technologies and experimental needs, with parameters that are strongly coupled. For example the strength of the undulator magnetic field is constrained by the magnet technology; higher energy photons require a smaller period and/or lower undulator magnetic field; the photon flux decreases with decreasing undulator magnetic field.

Undulator magnetic fields of less than 1 T are required to radiate photons with energies above 2 keV from 2.5 GeV electrons. Such magnetic fields can be achieved using permanent magnet undulators of proven design. Alternatively, superconducting undulators may achieve the design specifications and may provide simplified operations in adjusting polarization of the photon beam, for example in a helical device.

To achieve the required large photon flux per bunch, undulators with length of up to 6 m are under consideration. These have particular advantage in reducing the charge per bunch requirement. Manufacturing complexity may require that these undulators be segmented. A final design will be motivated by the need for performance and avoidance of unnecessary design/engineering, manufacturing, and reliability risks.

Synchronization

Several synchronization concepts have been considered. For the baseline design, the deflecting cavities are driven from a highly stable rf signal derived from a mode-locked laser oscillator that is also the origin of the pump laser pulses. Using feedback on all rf systems (rf gun, injector linac, main linac, deflecting cavities) control of the bunch arrival time with respect to the rf phase at the deflecting cavities is expected to be better than 1 ps. Each cavity in the linacs is individually powered and controlled with phase and amplitude feedback systems to provide optimal stability.

The recirculating geometry allows the use of timing signals generated by the electron beam in a prior pass to be used as triggers for lasers and detection systems in succeeding passes through the machine. Optical undulators may be used to provide these timing signals, as may broadband synchrotron radiation from bend magnets.

The exploration of the limits of synchronization of x-ray pulses from the recirculating linac-based light source will continue. Analysis to-date suggests that the baseline design will provide the required synchronization between electron bunches, x-ray pulses, and the pump lasers.

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